

# **Part I**

## **Initial Site Investigation For Nanotechnology: Investigating Site Parameters for Vibration, Noise, EMI and RFI Sensitive Facilities**

*Nanotechnology has been termed the “next industrial revolution.” Nanoscience deals with the fundamental principles of molecules and structures between one and 100 nanometers in length. A human hair is approximately 10,000 to 50,000 nanometers wide. World governments are competing to develop expertise in nanotechnology, investing approximately \$4 billion in 2004. The largest nanotechnology investors are the United States, Japan and Western Europe, with China coming up quickly. The National Science Foundation projects that annual global impact of nanotechnology will exceed \$ 1 trillion by 2015. The first important steps for nanotechnology facilities include site and facility assessments to see if the nanotechnology can be preformed on the site. This is the first part of a two-part article.*

### **Nanotechnology Sites and Facility Parameters**

Nanotechnology facilities are appearing rapidly at university campuses, government installations, and science parks around the world due to the extensive governmental and institutional competition to exploit the economic development advantages of this relatively new technology. “One SITE does not fit all” might be a good way to approach planning for nanotechnology. The research carried out in these facilities is highly sensitive to excessive vibration, noise, electromagnetic interference (EMI), and radio frequency interference (RFI), all which vary from site to site, as well as “interior” “contaminants” including, temperature, air quality, and life safety issues. All of these design issues must be identified and quantified as early as possible in order to minimize cost impact on the project. Sites have been rejected due to proximity of railroad tracks, traffic, power lines and electrical substations, and large mechanical systems in neighboring buildings. Even the construction of future nearby buildings at the campus or research park may require consideration during planning. The consequences of waiting too long to carry out nanotechnology parameter investigations can be quite dramatic. Many site factors may be accommodated during design, but only if identified early in the design process.

### **Overview of Nanotechnology Facilities and Site Concerns**

Once an institution, company, or community elects to investigate the potential of nanotechnology, the first step is to investigate the potential sites and their respective critical nanotechnology attributes. It is best to investigate each site attribute during periods of greatest impact, such as vibrations due to traffic during rush hour or periods with high truck traffic at high speeds. The objective is to define the magnitude and statistics of the “worst case” performance of each site parameter. Researchers may also need to know how the parameters vary over time.

Not all nanotechnology facilities are equally sensitive to environmental conditions. Work with theoretical or modeling aspects of nanotechnology tends to be insensitive to the environment. The opposite extremes occur with molecular manipulation and certain types of microscopy. In general, the site must be able to meet the

most stringent demands within the facility, or else expensive mitigation may be required in the design. (There are also cases in which mitigation simply is not practical.)

### **Vibration**

Potential sources of site vibration include vehicular traffic (both on-site and off-site), railroads and subway systems, construction (especially pile driving and vibratory compaction), and poorly isolated mechanical equipment in neighboring buildings. Some of these vibrations can be accommodated during design; others may require rejection of a site. (A large earthquake would likely interrupt research, but the researchers would likely have to evacuate the building.) Road maintenance becomes a critical factor, as vehicles crossing speed bumps, potholes, or rough snow-pack can cause some of the worst vibrations.

When the site is an existing building slated for renovation, then the above factors must still be considered, but there are several additional ones. Floors suspended over a basement (or crawl space) must be evaluated for vibrations due to personnel activities, particularly walking. The designers may also need measured structural properties, such as stiffness or resonance frequency. Slabs-on-grade need to be evaluated for stiffness and quality of the contact with the subgrade soil. Existing mechanical equipment that will remain after the renovation will be a source of vibration in the new facility, so it must be evaluated in the new context. (It may have been adequate in the context of the previous building, but not in a nanotechnology facility.)

### **Electromagnetic Interference (EMI)**

Nanotechnology equipment is very sensitive to both AC and DC magnetic fields. Direct Current (DC) sources include subways and trolleys, as well as moving ferromagnetic masses such as vehicles outside the building—including trains—and elevators, dumb waiters, and steel doors inside the building. These perturb the geomagnetic field of the earth generating time-varying DC fields that impact nearby scientific instruments such as electron microscopes, electron-beam lithography equipment, and focused ion beam systems.

Alternating Current (AC) magnetic fields are associated with the flow of AC electricity. This can be associated with power lines, transformers, switchgear, or the wiring inside a building. Electromagnetic induction occurs when time-varying AC magnetic fields couple with any conductive object including wires and electronic equipment, thereby inducing circulating currents and voltages. In susceptible electronic equipment and signal cables, electromagnetic induction generates electromagnetic interference (EMI), which is manifested as visible screen jitter in displays, hum in analog telephone/audio equipment, lost sync in video equipment and data errors in magnetic media or digital signal cables.

### **Radio Frequency Interference (RFI)**

Radiofrequency interference (RFI) is EMI for which the frequencies are those associated with radio transmission, generally between 100 kilohertz (KHz) and 50 gigahertz (GHz). One of the most common sources of RFI is the cellular telephone. In the US, the Federal Communications Commission (FCC) has legal jurisdiction over RFI. However, at present, there are no mandated RFI susceptibility standards in the US. The only standards are those associated with individual items of susceptible equipment. In Europe, there are applicable standards such as EN 61000-6-1. EMI/RFI consultants generally base their recommendations on the European standard, but are somewhat more conservative.

### **Noise Interference**

A number of processes (often the same ones that are highly sensitive to vibration) are highly sensitive to airborne noise. Some of the instruments are so sensitive that operators cannot even whisper during their use. In all but the most extreme cases, the building shell is adequate to attenuate site noise. One exception is aircraft noise. If the site is impacted by overflights by large aircraft (such as beneath takeoff or approach

paths for airports), then extra measures are required during the design, but the aircraft noise at the site must be measured so that appropriate designs are used. In the vast majority of situations, sound at audible frequencies is the primary concern.

### **Airborne Contaminants**

Most nanotechnology facilities include cleanrooms used for fabrication at the nanometer scale. This environment is inherently sensitive to airborne contamination by particulates or airborne molecular contaminants (AMCs). Generally, the facility's mechanical system will be designed to create an environment with adequate cleanliness, but assumptions are made about the quality of the air entering the building. If the site exhibits unusual airborne particles (such as dust from a cement plant, for example) or chemicals (a refinery, perhaps), then the extent and nature of the contaminants must be quantified.

### **Temperature Parameters**

Temperature fluctuation can pose a problem because at the exceedingly small scales of nanotechnology, very slight changes in temperature can lead to relatively large changes in dimensions. If a researcher wants to position a molecule at a particular location, a variation of one tenth of a degree between the time the molecule is "grabbed" and the time it is placed will cause it to be placed in the wrong location. Generally, any building can be designed to withstand very large changes in temperature over a large period of time (such as daytime to nighttime) but very sophisticated temperature controls are required to maintain the temperature stability required for some processes. In extreme cases, it may be necessary to control temperatures to within 1/100 of one degree Celsius. Thermal stability is a critical issue during building design, but generally not an issue for site selection.

### **Humidity Parameters**

At this time, the constraints on humidity in a nanotechnology facility are not as stringent, relatively speaking, as those on vibration, noise, EMI/RFI or temperature stability. This is not an issue of concern for a site study, but must be addressed by the Mechanical Engineer.

### **Site Investigation for vibration and noise on site and in buildings.**

A successful site vibration investigation requires three things: (1) knowledge of (or an estimate of) the vibration criteria for the facility; (2) appropriate instrumentation, which includes specialized sensors and amplifiers; and (3) adequate training and/or experience.

Vibrations are measured with a low-frequency (or "seismic") sensor of very high sensitivity, placed on a stake driven into the ground, or on a curbstone or other feature making good contact with the ground. Measurements are generally made at several locations within the footprint of the proposed building. Vibrations in the vertical direction are measured at all locations, but horizontal vibrations are sometimes measured at only a few of these locations. The data are processed in a spectrum analyzer such that plots of amplitude versus frequency are produced.

On a "green field" site, measurements are made of steady-state ambient vibrations and during representative events that might generate vibrations, such as passages of trains or motor vehicles. When evaluating an existing building, one adds to this list measurement of vibrations due to walking and (perhaps) other personnel activities. In an existing building, the existing mechanical system is virtually always the predominant source of vibration. The vibration consultant can identify individual items of equipment causing excessive vibration. If the building is to be gutted for the renovation, the study should be carried out with the mechanical systems turned off (if possible).

There are two approaches to assessing site noise. Obviously, one can measure it. However, in the case of aircraft noise, the airport may serve many different aircraft types, and some aircraft are noisier than others. The airport can often provide a typical mix, and if the noise is measured at the site for several known aircraft, the results can be scaled to represent the other aircraft. Another significant source of site noise is an alarm (such as an evacuation alarm) being exercised. These are deliberately noisy and intrusive, and an owner may or may not wish to eliminate it via sound attenuation in the building shell.

### **Critical factors you need to know**

In order to assign a criterion, the vibration consultant must have some knowledge of the instruments (or types of instruments) that are to be used. (Occasionally, owners or lab consultants will arbitrarily pick criteria based upon what they've been told or on experience with past projects. This has led to site criteria that were too stringent, and others that weren't stringent enough.) In order to approve a site, the consultant must know that the site survey has captured the majority of representative vibration- and noise-generating events; and either (1) the site meets the most stringent criterion for the facility, or (2) the building can reasonably be expected to attenuate the vibration or noise. The attenuation provided by a building (for either vibration or noise) is a function of frequency, and a certain amount of experience is required to estimate it.

### **Typical problems encountered**

The most challenging measurement problems (other than simple equipment malfunctions) have been weather. Rain causes signal connections to short out or generate noise. Temperatures well below freezing cause thermal stresses within the sensors that appear on the analyzer to be vibrations (to the untrained eye). Frozen ground can provide a challenge for sensor placement. High water tables (i.e., standing water) poses two problems: (1) difficulty getting a good attachment to the ground, and (2) poor attenuation of vibrations from a distance.

If a facility is to be successful, the aesthetics of a building (and perhaps its political value as a landmark) may have to be subordinated to the ability to provide a good environment. In several instances, considerable pressure was placed on using a particular site (because it would "make a good architectural statement there") or because it would help facilitate inter-agency cooperation. Generally, if the researchers are allowed to enter the argument, they win. At least two sites for nanotechnology facilities have been rejected because of rail vibrations. One location was expedient for the internal politics of the institution. The other (at a different institution) was on "neutral" ground that facilitated easier collaboration with researchers outside the organization. Two sites were rejected because on-site traffic caused excessive traffic during certain times of the day. One site was rejected because of the proximity of a building with mechanical equipment causing excessive vibration. In all of these cases, the researchers insisted that environment had to take precedent over everything else, if the building was to be successful in its mission.

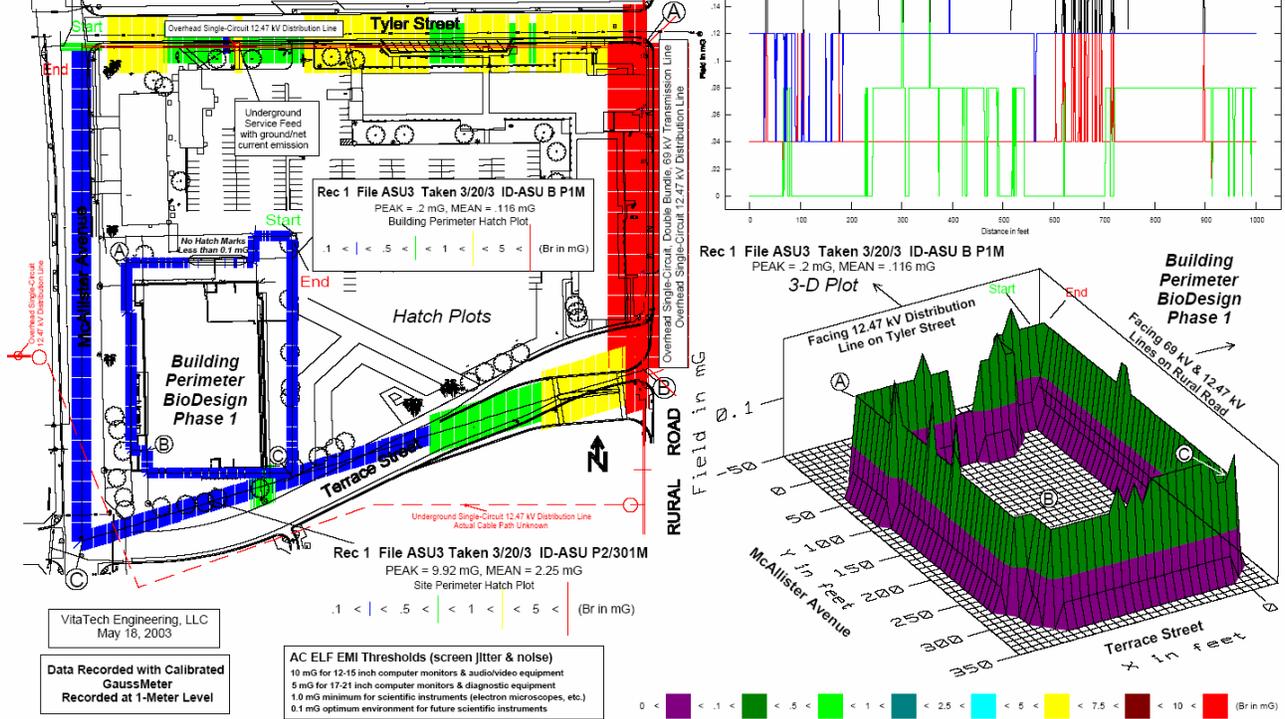
At least two nanotechnology facilities are impacted by aircraft noise. In both cases, this was known in advance, and the affected portions of the buildings were built as "shell within a shell", increasing the attenuation. Neither site had to be rejected. Two facilities have required modifications to streets or traffic patterns to reduce traffic impact (particularly buses). One otherwise-logical site was immediately vetoed when it was discovered that the same research park had an earthquake simulator (a "shaking table"). Two facilities will be the first or second facilities in new research parks, and the Owner has had to implement limits on construction activities and setback distances for future buildings.

### **Site Investigation EMI and RFI on site and in buildings.**

VitaTech—located in Springfield, Virginia—is a firm specializing in EMI and RFI investigations. VitaTech normally performs a full spectrum EMF site survey at a proposed nanotechnology building site as well as surrounding areas to identify all sources of DC, alternating current extremely low frequency (AC ELF) and



Figure #2 - AZ BioDesign, Phase 1 - Building Perimeter Plot  
 AC ELF Magnetic Flux Density Data - recorded at 1-Meter Level  
 Arizona State University, Tempe, AZ - Data Recorded 03-20-03



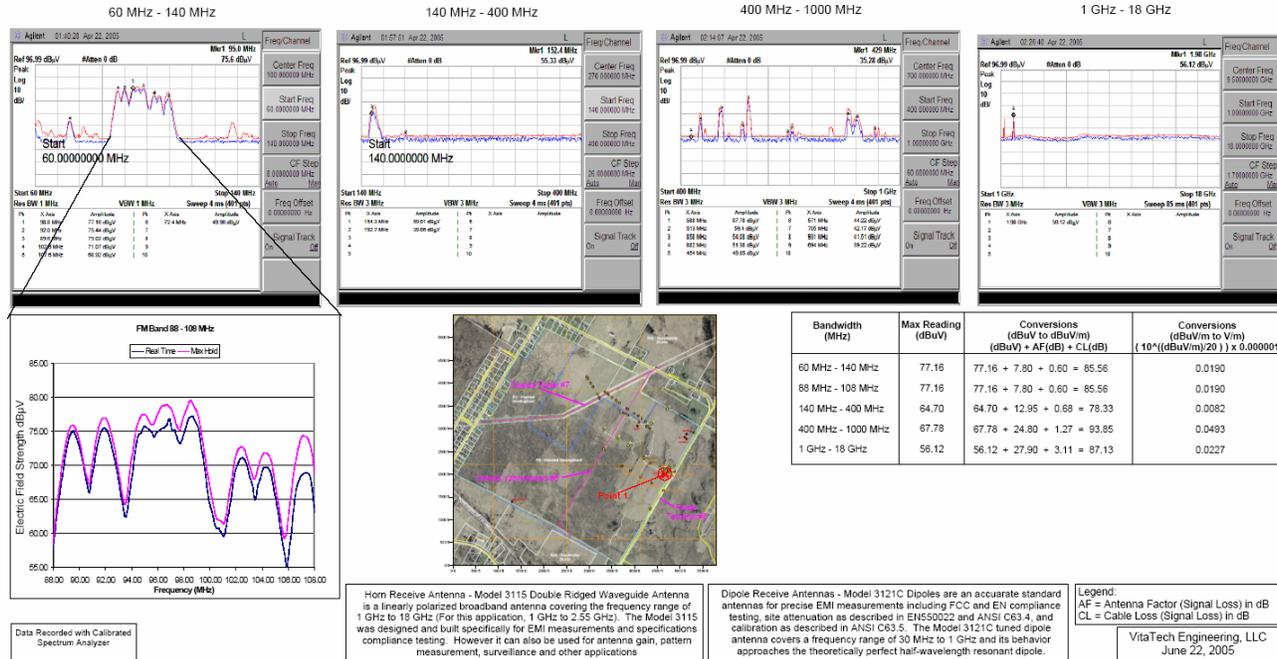
Wideband timed electric field strength data should be recorded at selected locations around the site to identify potential RFI emission sources, such as antenna farms, commercial TV/FM/AM broadcast emitters, mobile and fixed microwave and cellular towers, and weather radar systems. If the terrain is relatively flat, a single point at the center of the property is the best location for RF data collection. Timed electric field strength levels should be recorded from 100 kHz to 18 GHz around the site. When detailed RF spectral information is required because the site is in a remote location or exceeds one of the recommended RFI thresholds, it is necessary to use a portable spectrum analyzer with calibrated dipole and microwave horn antennas. Figure 3 shows an example of a spectrum site survey.

**Figure #3, Site Survey of Chip FAB  
Point 1 - RFI Testing 60 MHz to 18 GHz**

Peak electric field strength RF levels were converted into volts-per-meter (V/m) as measured with the calibrated antennas and Agilent Technologies 5553E Spectrum Analyzer. The objective is to investigate sources of radio-frequency interference (RFI) over a wide bandwidth. It should be noted that 3 V/m is the industry standard RFI threshold and 1 V/m the medical/scientific instrument RFI threshold.

**IEEE C63-94 RF Immunity Standards**  
**Electromagnetic Interference (EMI)**  
 Radiated AM Immunity: 10 V/m 450-520 MHz and 800-950 MHz @ 80% AM  
 Radiated Pulse Immunity: 3 V/m 1.59 GHz 50% Duty Cycle  
**Signal Line Ports & Ports for Process Measurements & Control**  
 RF Common Mode: 3 V/m 0.15 - 100 MHz @ 80% AM  
 Input/Output DC/AC Power Ports  
 RF Common Mode: 3 V/m 0.15 - 100 MHz @ 80% AM

Max Hold Method - displays the cumulative recorded RF signals over time including digital and CW short-term pulse sources (pagers, etc.).



The final EMI/RFI site survey report should present the recorded emission data in 2-D and 3-D graphical format overlaid on the site plan and floor plans. The author should discuss the potential EMI/RFI impact of the ambient data on the new facility and future research tools. A recommend remediation strategy (i.e., magnetic and/or RF shielding, increased separation distance to sources, active-cancellation technology, etc.) should be presented to control the EMI/RFI impact where the thresholds exceed acceptable levels.

**Critical factors you need to know.**

One of the most important factors is to correctly decipher the manufacture’s EMI performance requirement. Placement of each scientific tool and instrument depends on the actual EMI susceptibility under defined thresholds, which are often not easy to ascertain from the manufacturer’s performance criteria. As with vibration and noise, an experienced consultant will have standard recommended limits based on experience with particular settings which can be used during design, but a space evaluation for a particular instrument should be based upon the requirements of that instrument. Using the simulated emission profiles and the correct conversion formula, it is possible to identify the appropriate areas for each tool *if the correct EMI susceptibility figure can be ascertained from the manufacturer’s specifications. Therein, lies the real EMI challenge.*

**Problems that have been encountered.**

Professional grade gaussmeters and fluxgate magnetometers have NIST-traceable calibration documents. However, several custom designed magnetometer systems are based on a fluxgate probe connected to signal processing systems. Unfortunately, such instruments generally do not have NIST-traceable calibration certificates verifying the accuracy of the custom system, especially at the bottom of the dynamic range wherein lies the sensitivity of many instruments for nanotechnology. Recommendations for expensive mitigation systems (i.e., magnetic shielding, active field cancellation system, etc.) may be presented to the client based upon the assumed accuracy of these systems. It is recommended that the client always request a

NIST-traceable calibration certificate from the EMF survey consultant prior to a decision to purchase a mitigation solution based upon recorded site levels and critical instrument specific EMI susceptibility requirements.

## **Part II:**

# **Initial Site Investigation For Nanotechnology: Investigating Site Parameters for Vibration, Noise, EMI and RFI Sensitive Facilities**

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## **Part I Overview**

In the first part Vibration, Electromagnetic Interference (EMI), Radio Frequency Interference (RFI), Noise Interference, Airborne Contaminants, Temperature Parameters, and Humidity Parameters were investigated. Critical factors regarding measuring and avoiding problems were reviewed. Samples of EMI and RFI investigations were discussed.

## **Case Studies of Site Investigations for Nanotechnology**

### **Advanced Measurement Laboratory, Gaithersburg, MD**

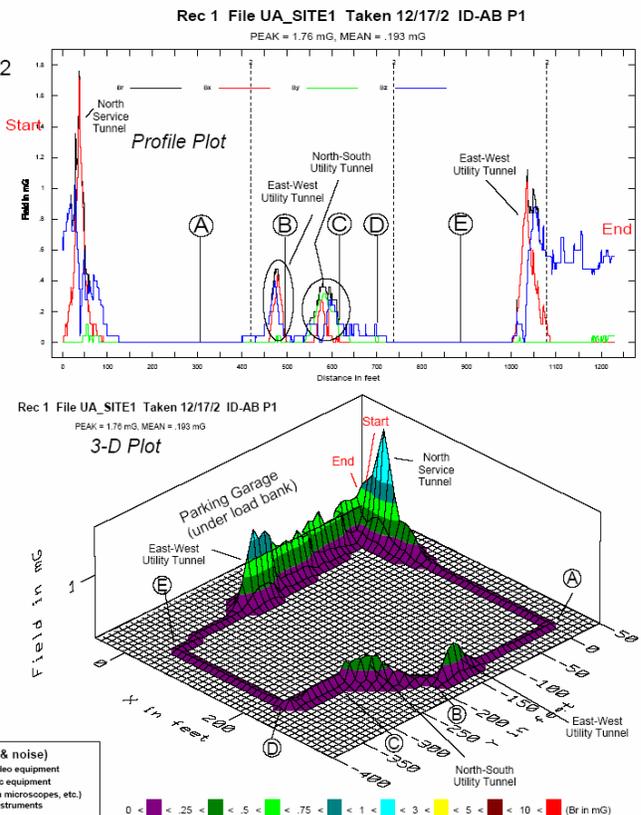
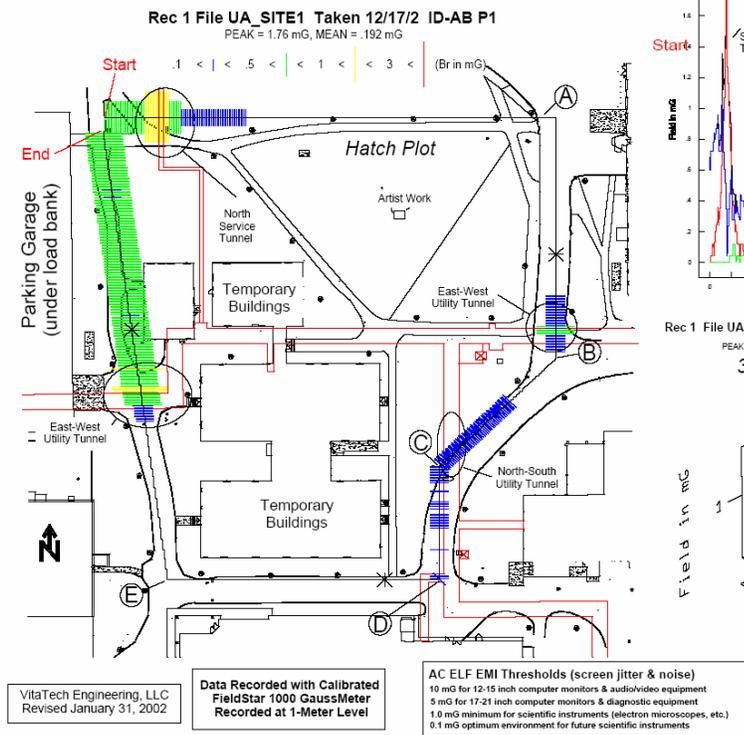
The Advanced Measurement Laboratory at the National Institute of Standards and Technology (NIST) in Gaithersburg, MD, is really a facility for the study of measurement science, but has become the prototype for many nanotechnology facilities. The site vibration and noise survey for this facility was probably the most extensive ever carried out for a technical building. Measurements were made continuously over 24-hour periods and analyzed for both statistical variation and time variation. Moreover, this was done for two sites, because the initially preferred site had vibrations that were exceeding the requirements part of the time. Ultimately, the scientists were involved in the final selection, basing the decision on a comparison of the statistical variation of a single frequency band.

### **National Institute for Nanotechnology (NINT), University of Alberta Canada**

The 2002 EMI/RFI site survey at the site of the National Institute for Nanotechnology (NINT) at the University of Alberta Canada demonstrates how problems can be identified at a site, and the problems

themselves mitigated, rather than requiring expensive shielding. The proposed NINT site had several underground utility tunnels with emissions as shown in Figure #4. The perimeter data path had an average level of 0.192 mG and a 1.76 mG maximum peak 1-meter above the small north service tunnel (near Start point). A second peak of 1.1 mG appears near the parking garage above the east-west utility tunnel, which bisects the proposed site. An unknown ground/net current travels in the north service tunnel meandering southward to the east-west utility tunnel and then west to the parking garage. Two smaller peaks appeared along the perimeter path: 0.5 mG above the east-west utility tunnel at point B and 0.4 mG above the north-south utility Tunnel at point C. During the east-west utility tunnel inspection, ground currents were traveling on #8 stranded bare-copper grounding conductor mounted to the concrete ceiling creating a ground path with the metal pipes and conduits. VitaTech recommended using an experienced electrical contractor to measure and trace the ground/net currents at various locations around the loop, isolate the sources/causes, remediate (insert dielectric/isolation couplers in water lines, reroute and/or disconnect redundant grounding conductors, etc.). The work was successful and the ground/net current emissions are not an EMI threat to the NINT building currently under construction.

Figure # 4 - NanoBuilding Site - Perimeter Plot  
AC ELF Magnetic Flux Density Data - recorded at 1-Meter Level  
University of Alberta, Edmonton, Canada - Data Recorded 12-17-02



## Planning Issues

Nanotechnology facilities generally place such stringent demands on the building's environment that it is wise to determine feasibility as early as possible, particularly if an existing building is being considered for renovation. Just as an existing building must provide adequate headroom for equipment and MEP, or adequate structural capacity, it must also provide an environment compatible with the environmental requirements. Many deficiencies in vibration or EMI can be corrected, but at some added cost to the facility. There may be other deficiencies that must be identified as early as possible.

The facility must also have adequate scale to allow appropriate distance between sources of vibration and EMI (such as mechanical or electrical rooms, or elevators) and the sensitive research areas. Mechanical spaces in which air handling equipment will reside must be large enough to allow both fan housings and duct silencers, especially if there will be highly noise-sensitive spaces. Ducting may be oversized compared to conventional buildings, and the ducting will require isolation hangers.

In many ways, a green field site is somewhat easier to handle, as the design team usually has more control over the setting. In addition to evaluating vibration, noise, EMI and RFI at a site, the site should be evaluated with an eye to making sure it is large enough. Adequate open space must be allowed around the building such that distance can buffer the facility from on-site sources. Buffer zones can protect the facility from vibrations from streets and construction of other buildings, and from EMI from power lines and substations.

The vibration and EMI/RFI surveys should be carried out as early in the design process as possible. It is not unlikely that a site may be rejected, and this can lead to additional costs if the design effort has progressed to the point of becoming site-specific.

Some EMI/RFI rules are simple to follow: locate all high current electrical gear (transformers, secondary feeders, switchgears, etc.) and DC EMI sources such as elevators, parking lots and roads at the opposite end of the building from the high resolution imaging suites and tools. All high power RF emissions sources within the building must be in an RF shielded room supplied with EMI/RFI filtered electrical power to minimize conducted emissions throughout the building. The complete EMI/RFI rules list is rather long with hundreds of do's and don'ts, but in the end a low EMI/RFI environment in the imaging tool areas is achievable when a comprehensive EMI/RFI site survey, electrical power simulations, and detailed mitigation assessment are performed for the site of a new nanotechnology facility.

## **Future Trends**

### **More Demanding Instruments are being Developed.**

In the semiconductor industry, the demands on a building have reached a point of stability over time, because the environmental requirements are usually accommodated with the production equipment itself. This is not the case with the cutting-edge research instruments used in nanotechnology. There is a growing set of instruments that will function correctly on only a minority of the available sites. The current vibration standard for nanotechnology is that developed for the Advanced Measurement Laboratory at NIST, but several instruments have come along for which that standard is inadequate. Similar challenges arise for EMI/RFI.

### **Potential for more Underground Facilities.**

The sites of about half the existing nanotechnology facilities did not meet the NIST standard prior to construction. Depending on construction type, the building may be able to improve on the pre-construction site ambient, but it gets progressively more expensive. We will probably see more facilities going underground, following the lead of NIST (where the sensitive wings were 12m below the ground). Two facilities that have committed to go underground (despite the cost) are one at the University of Oregon and another at the University of Alberta. The underground environment provides a more stable thermal environment (no sun, no wind) as well as a much quieter vibration environment.

### **Need for lower EMI/RFI ambient environments.**

Higher resolution imaging tools demanding lower and lower EMI/RFI ambient environments. Therefore, shielding will become a requirement, rather than an option. Laboratories and imaging rooms can be designed to 1 mG and less without expending considerable resources. Environments under 1 mG to 0.1 mG demand careful planning and expensive EMI control strategies while achieving 0.01 mG demands a magnetically shielded room to guarantee long-term stability and optimal tool performance as the site conditions (i.e.,

circulation of ground/net currents, new EMI/RFI sources, etc.) eventually degrade during system-wide maturation.

### **Need for Universal EMI/RFI testing / susceptibility protocol.**

A universal EMI/RFI testing and susceptibility protocol for scientific imaging tools should be implemented by the industry to minimize confusion and ensure optimal performance when a multi-million dollar instrument is to be installed in a nanotechnology research building.

### **Federal Facilities will be followed by industrial leaders.**

The federal investment in nanotechnology facilities will probably be limited to the five centers being built by the Department of Energy. Many of the “top tier” schools have (or are building) dedicated facilities, and a growing cadre of other institutes are jumping on the bandwagon. Private industry, which has more money to spend, is standing back and letting research happen in the public sector. Once the marketplace gets better defined, then we will see organizations like Intel, IBM and Motorola taking a more proactive role than they have to date.

### **“Speculative” Nanotechnology facilities.**

A growing number of nanotechnology facilities are speculative—what some are calling “build it and they will come” facilities. In these cases, an organization will want to compete in the nanotechnology sector, but may not currently have any researchers. The organization believes that by having a good facility, they will be more likely to attract qualified researchers, who will then attract funding. To some extent, this may be true, but it is harder to define a generic facility than one that has some specific thought behind it. This is particularly true with regard to the more sophisticated environmental requirements (ultra-quiet vibration and noise, shielding for EMI, and very tight tolerances on thermal stability). The most critical part of defining criteria is a close interaction between a specialty consultant and the researchers, probing what environmental features really are justified. The very best facilities, such as the one at NIST, result from a close collaboration between the researchers and the design team, extending over a significant part of the design process.

### **Conclusions**

Site evaluation of vibration, EMI and RFI is absolutely essential at all proposed nanotechnology sites, whether green field or existing building. Today’s scientific instruments demand very “quiet” environments for maximum resolution and optimal stability during demanding nano- and pico-technology research. Identifying the vibration and EMI/RFI problems before construction will substantially reduce the cost to mitigate, perhaps by a factor of 2 to 3 times. It is significantly less expense and more effective to move the laboratory during the design phase than shield the EMI source after the building is operational. In some cases, a vibration or EMI source cannot be modified. When space is at a premium, RF and magnetic shielding are very effective EMI/RFI control methods and cost effective when constructed with the building.

Out of fifteen nanotechnology facilities, the initial site was rejected for excessive vibration in about 20% of the cases. Several more were marginal, but were used anyway for various reasons. Only about half of them met the NIST criterion, but all met the most stringent vibration used in the semiconductor industry. By comparison, less than 2% of sites for semiconductor facilities are rejected for these reasons.

Only 10% of the proposed building sites are not EMI/RFI acceptable because the ambient emission levels exceed the recommend thresholds due to the proximity of highways, electric and diesel trains, overhead and underground transmission/distribution lines, substations, high power commercial broadcast antennas and other, invisible, but problematic, EMI/RFI sources.

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